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Flatland in flames: a two-dimensional crown fire propagation model

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Abstract. The canopy bulk density metric is used to describe the fuel available for combustion in crown fire models. We propose modifying the Van Wagner crown fire propagation model, used to estimate the critical rate of spread necessary to sustain active crown fire, to use foliar biomass per square metre instead of canopy bulk density as the fuel input. We tested the efficacy of our proposed model by comparing predictions of crown fire propagation with Van Wagner's original data. Our proposed model correctly predicted each instance of crown fire presented in the seminal study. We then tested the proposed model for statistical equivalence to the original Van Wagner model using two contemporary techniques to parameterize canopy bulk density. We found the proposed and original models to be statistically equivalent when canopy bulk density was parameterized using the method incorporated in the Fire and Fuels Extension to the Forest Vegetation Simulator (difference $< 0.5\,\mathrm{km\,h^{-1}}$, $\alpha = 0.05$, $n = 2626$), but not when parameterized using the method of Cruz and others. Use of foliar biomass per unit area in the proposed model makes for more accurate and easily obtained fuel estimates without sacrificing the utility of the Van Wagner model.

Additional keywords: canopy bulk density, crown fire, equivalence test, foliar biomass per unit area, FBA.

Introduction

Satisfactory modeling of fire spread is challenging because fuels are inherently three-dimensional, and data of the necessary resolution are usually unavailable (Cruz *et al*. 2003; Keane *et al*. 2005). Credible simplifications of the available models may provide opportunities for defensible modeling of fire spread using more commonly available data.

In the present paper, we focus on the challenge of modeling crown fire propagation. Particular difficulty arises in modeling crown fires because crown fires can exist in either 'passive' or 'active' modes. In passive crown fires, individual trees or groups of individuals ignite and burn from the bottom to the top of the crown, resulting in mixed impacts on the environment (Ryan and Noste 1983). In active crown fires, the combustion propagates as a solid wall of flame through a landscape filled with trees, in conjunction with a surface fire (Van Wagner 1977). Furthermore, this combination of active canopy and surface fire often burns at high intensity, having significant impact on soils, vegetation, and wildlife habitat (Grier 1975; Ryan and Noste 1983; Romme *et al*. 1995; Haggard and Gaines 2001). Such fires may exhibit flame lengths exceeding 30 m, with rates of spread exceeding $50\,\mathrm{m\,min^{-1}}$ (Stocks *et al*. 2004). Active crown fire poses great risk to fire personnel, the public, and private property (Scott 1998; Clark *et al*. 1999; Scott and Reinhardt 2001). For these reasons, fuel managers design treatments to alter canopy fuels so that the fuels will not sustain crown fire (Hof and Omi 2003; Scott 2003; Peterson *et al*. 2005). Managers also wish to predict and understand the behavior of these fires (Stocks *et al*. 2004). Such applications require knowledge of the minimal conditions required to sustain the propagation of a crown fire, in order to inform mitigation treatments and the assessment of hazard to fire personnel during active fires.

Most fire planning tools and spatially explicit fire models depend on Van Wagner's (1977) model, hereafter referred to as VWcbd. VWcbd is used to characterize the minimum conditions necessary to sustain active crown fire (Van Wagner 1977; Keane *et al*. 2000; Scott and Reinhardt 2001; Finney *et al*. 2003; Reinhardt and Crookston 2003; Finney 2004).

VWcbd relies on canopy bulk density (CBD), a three-dimensional metric of available canopy fuel for combustion. CBD is defined as the dry weight of the available canopy fuel per unit volume (see e.g. Cruz *et al*. 2003). Precisely estimating CBD data can be prohibitively expensive; for example, Scott and Reinhardt (2005) report nearly 1000 person-hours required to physically measure several canopy biomass variables (including their vertical distribution) to calculate canopy fuel CBD for a single 10-m radius plot. Operationally, CBD is estimated using tree-lists and allometric equations.

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The challenge of unambiguously defining and measuring CBD is complicated by the fact that tree crowns are fractal objects, with fractal dimension between 2 and 3 (see e.g. Mandelbrot 1983; Zeide 1998). In order to define the volume that encloses the canopy, arbitrary decisions must be made about where the vertical profile of the canopy begins and ends. Further complications are added by slipperiness in the definition of crown length.

This expense to physically measure the volume space used in CBD calculations has made it difficult to field-test, calibrate, refine, or even observe the efficacy of the model as put forth by Van Wagner (1977) (Keane *et al*. 2005). Other research has attempted to quantify CBD for given forest systems, but with mixed success (Keane *et al*. 2000, 2005; Fule *et al*. 2001; Gray and Reinhardt 2003; Hummel and Agee 2003; Riaño *et al*. 2003, 2004; Perry *et al*. 2004; Falkowski *et al*. 2005; Peterson *et al*. 2005).

We now broadly sketch the logic of the VWcbd crown fire model, drawing extensively from Van Wagner (1977). The model for the *initiation* of crown fire depends on crown base height, foliar moisture content and fireline intensity (or flame length). By definition, once crown fire has been initiated, then a wall of flame exists from the base of the tree crown to the top of the tree crown. At this point, a separate crown fire *propagation* model states that the spreading crown fire must consume at least a minimum amount of fuel per unit time by consuming nearby fuel sources. If crown fire moves to a nearby source of fuel with insufficient quantities of fuel present, then the crown fire will fall back to the ground as a surface fire, which renders the crown fire propagation model irrelevant. Therefore, a central consideration for crown fire modeling is whether enough fuel is adjacent to an existing crown fire to continue the fire's propagation, or if the fire will fall back to the ground as a surface fire.

A key definition for our study is that combustion must be occurring along the entire length of the tree crown for crown fire to be initiated (Van Wagner 1977). If crown fire is initiated, then the key criterion for propagation is whether enough fuel exists in the space adjacent (in an x,y-coordinate system) to the combusting tree crowns for the crown fire to spread. The vertical distribution of the adjacent fuel is of little relevance in the propagation model because there is no explicit parameter for vertical distribution in the Van Wagner model. Indeed, the effect of the vertical distribution of fuel on crown fire propagation remains to be determined more generally.

In the present study, we propose a model that does not require any assumptions about how the vertical distribution of fuel might influence crown fire propagation, and requires as input a single metric of horizontal fuel availability. Our approach is logically consistent with Van Wagner's crown fire propagation model, but it avoids the requirement of CBD calculation, which introduces questionable and unproved assumptions about the effect that the distribution of fuel in the vertical dimension has on crown fire.

In the following sections, we develop VWfba, a modified version of VWcbd that uses foliar biomass per unit area (FBA) as a fuel input. We compare VWfba with VWcbd, using two different CBD estimation methods, to assess whether FBA can be used with confidence in existing fire modeling applications with minor modification. We conclude with a comparison of the two models, some reflections on the possible advantages and disadvantages of VWfba, and a tentative prescription for further work that would be necessary before VWfba could be adopted in a field setting.

Crown fire defined

Agee and others (2000) describe a conceptual crown fire model using 'a stationary wall of flame with a conveyor belt carrying fuel into the flame'. The conveyor belt must maintain a rate greater than minimum critical rate of spread (cROS) in order to deliver a sufficient quantity of combustible fuel per unit time to maintain the wall of flame in the canopy space (Van Wagner 1977).

Van Wagner relied on the previous work of Thomas (see Van Wagner 1977) in the development of modeled crown fire interactions. The resulting relationships between fuel, flame front rate of spread, and the *minimum* fireline intensity necessary to maintain crown fire are very similar to the work of Byram (1959). Byram's (1959) surface fire index relates fireline intensity, the rate of spread of a flame front, and the quantity of *combusted* fuel (Byram 1959; Scott and Reinhardt 2001). By representing the flame front as a line moving at some rate across a plane of homogeneously distributed fuel mass (per unit area) (multiplied by a constant heat yield), the result is a fireline intensity that is the product of the rate of flame movement and the homogeneous fuel (per unit area) (Byram 1959). Like Byram's (1959) index, the VWcbd assumes a homogeneously distributed fuelbed, albeit through a volume rather than across an area (Van Wagner 1977). The assumption of a homogeneous fuel bed with a constant heat yield per unit of fuel makes VWcbd synonymous to Byram's (1959) index in concept, and makes the VWcbd mathematical model structurally identical (though VWcbd uses different units).

However, the Van Wagner (1977) model does differ in that it is calibrated to the *minimal* conditions necessary for active crown fire to persist and in its use of fuel quantity per unit volume instead of unit per area. Van Wagner assumed that the fuel present in a stand would have a constant heat of ignition (per unit mass), and thus avoided the necessity of calculating the energy in the propagating heat flux. This assumption changed the crucial element to a simple argument that relates only the critical quantity of fuel consumed per unit time required for flame maintenance, divided by the available fuel quantity (Eqn 1). The outcome of this equation is the definition of a cROS (represented by R_o in Eqn 1) required for the fire to consume the available fuel (d) such that the critical mass flow rate (S_o) is satisfied.

$$R_o = \frac{S_o}{d} \qquad (1)$$

where R_o, cROS for active crown fire ($\mathrm{m\,s^{-1}}$); S_o, critical mass flow rate for crown fire ($0.05\,\mathrm{kg\,m^{-2}\,s^{-1}}$); d, foliar (canopy) bulk density ($\mathrm{kg\,m^{-3}}$).

Van Wagner's definition of crown fire as a wall of continuous flame from bottom to top of the canopy must be met to satisfy the implicit assumption that crown fire has been initiated (Van Wagner 1977; Scott and Reinhardt 2001). The use of a single value to represent a distribution of fuel through the canopy space removes any influence that the vertical distribution of fuel may have on crown fire, requiring a second assumption that horizontal crown fire propagation occurs regardless of the vertical distribution of the fuel. The quotient resulting from the division of the available fuel by volume (the definition of CBD) is simply a fraction of the total fuel load instantaneously available (the sum across a plane (with dimensions of the wall of flame) is still available for combustion) and includes no effect that the vertical distribution may (or may not) have on crown fire. In the best situation, one must know the volume used as the canopy space in order to calculate the total amount of fuel available for crown fire propagation. In the worst situation, the CBD has no clear relationship to canopy volume and the total available fuel cannot be reconstructed. Regardless, Van Wagner's crown fire propagation model is a one-dimensional model by virtue of the dimension of its output ($m\,s^{-1}$). Although the equation is expressed with units connoting a two-dimensional simplification of a three-dimensional process, it need not depend solely on a volumetric-based fuel input.

We assume that the Van Wagner (1977) model appropriately relates the basic properties necessary to describe the lower boundary conditions required for active crown fire combustion, namely, that an active crown fire spreading between two points on the landscape must consume a minimum quantity of fuel per unit time in order to persist as a crown fire. Naturally, the quantification of fuel is vital to a model of the combustion process. However, we argue that the quantification need not incorporate the vertical dimension into the fuel metric as traditional canopy fuel methodologies have done.

We use Van Wagner's (1977) published data to recalibrate the model for use with FBA in place of the standard CBD input. The VWcbd and the VWfba models are applied to a region-wide non-spatial Forest Inventory and Analysis (FIA) database collected from the Inland Northwest and an equivalence test is used to compare the estimates of cROS from the VWcbd and VWfba models.

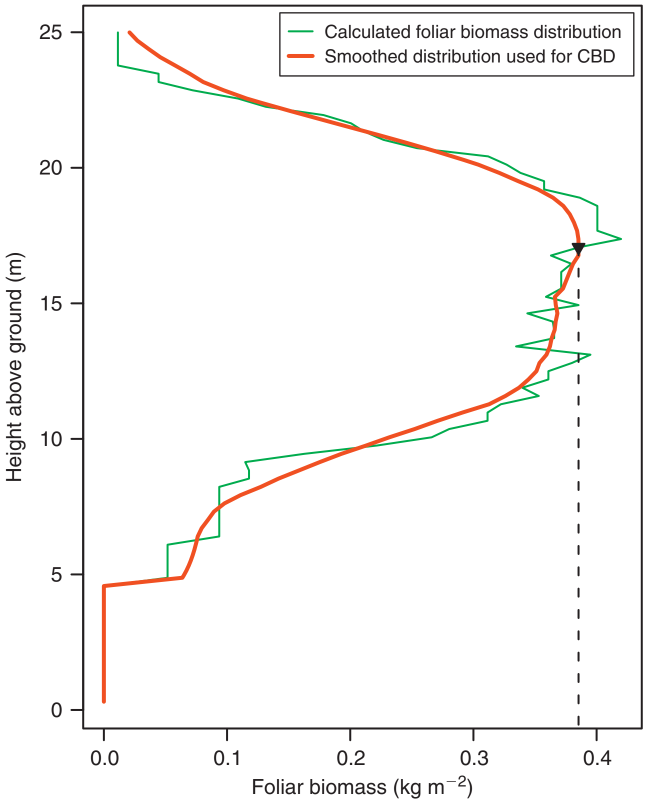

Fig. 1. Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator methodology of canopy bulk density (CBD) calculation. The maximum of the 3.97-m (13-foot) running mean (marked with a star) read from the *x*-axis is the value used as the 'effective CBD'.

Methods

In this section, we introduce two methods used to calculate the fuel input necessary for VWcbd. We compared only the Fire and Fuels Extension (FFE) to the Forest Vegetation System (Reinhardt and Crookston 2003) and Cruz *et al*. (2003) methods because they represent the two distinct approaches to estimating CBD. We then modify the existing VWcbd for the use of foliar biomass to create the VWfba model. Finally, we introduce our data and the statistical methods used to test the equivalence of the VWcbd and VWfba.

Summary of CBD methods

The complex FFE method is widely used by many US federal land managers and researchers (Hummel and Agee 2003; Perry *et al*. 2004; Andersen *et al*. 2005; Falkowski *et al*. 2005; Peterson *et al*. 2005). This use is facilitated by the FFE implementation in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) computer software (Reinhardt and Crookston 2003) and the proprietary *Fuels Management Analyst Plus* suite of computer software (FPS 2001).

When applied to a stand inventory list, FFE calculates the foliar biomass (and 50% of the 0–6.3 mm-branch wood) assuming a constant density of biomass through the length of the individual tree-crown space. FFE calculates the amount of biomass contained in every 0.3048-m (1-foot) slice above the ground within the crown volume space for each tree (Scott and Reinhardt 2001). Finally, the biomass for all individuals in the stand is summed within each 0.3048-m slice above the ground (represented in Fig. 1). This sum represents stand biomass ($kg\,m^{-2}$) distributed by height above ground (m), i.e. vertical distribution of foliage within the canopy space (Sando and Wick 1972). Further detail can be found in Reinhardt and Crookston (2003) and in Scott and Reinhardt (2001).

FFE calculates the maximum 0.3048-m (1-foot) increment of a 3.96-m (13-foot) running mean applied to the vertical profile of foliar biomass (see Fig. 1) (Reinhardt and Crookston 2003). This produces an effective CBD value, which differs from the traditional CBD definition (Scott and Reinhardt 2001). Effective CBD provides a value that is the maximum of a running average (Fig. 1) and represents the greatest average CBD value, presumed to be the least-resistant stratum for crown fire propagation through a stand (Scott and Reinhardt 2001). Despite the lack of direct correspondence to the CBD definition, effective CBD is frequently used as input to VWcbd (Scott and Reinhardt 2001).

Cruz *et al*. (2003) advocate summing the foliar biomass for all trees in a stand and dividing this by the product of the average vertical crown length multiplied by the area of the stand. Biomass is assumed to have equal distribution through the volume of

Table 1. Summary of data taken from Van Wagner (1977) used for model recalibration
CBD, canopy bulk density; ROS, rate of spread

Test fire name	Fire type	Basal area ($m^2\,ha^{-1}$)	Trees (ha^{-1})	Tree height (m)	Height to live crown (m)	Biomass ($kg\,m^{-2}$)	CBD ($kg\,m^{-3}$)	Actual ROS ($m\,s^{-1}$)
C6	Active	50	3200	14	7	1.8	0.23	0.46
C4	Active	50	3200	14	7	1.8	0.26	0.28
GLB	Active	25	1800	18	6	1.2	0.11	0.41
R1	Developing	50	3200	14	7	1.8	0.23	0.18

the canopy. Such an algorithm makes arbitrary yet necessary assumptions about the three-dimensional shape of the canopy. This method appears to be similar to the method used by Van Wagner (1977) for calculation of experimental fuels data. We refer to this method as the 'Cruz' method for the remainder of the present paper.

Modification of Van Wagner's model

To create VWfba, we modify VWcbd (Eqn 2a) (Van Wagner 1977) by altering the mass flow rate (S_o, Eqn 2a), which represents the minimum quantity of fuel required to be combusted per unit time to sustain crown fire propagation. To determine S_o, Van Wagner identified forested stands for crown fire experimentation and recorded stand information including stems per hectare, basal area, tree height, height to crown base, and biomass per unit area (Table 1). Three of the four stands listed in Table 1 were experimental fires (C6, C4, R1) in a red pine plantation, while the fourth (GLB) was a wildfire in a jack pine forest. Three of the four fires were judged to burn as active crown fires (Van Wagner 1977) (Table 1).

$$R_o\ (\mathrm{m\,s^{-1}}) = \frac{S_o}{d} = \frac{0.05\ (\mathrm{kg\,m^{-2}\,s^{-1}})}{d\ (\mathrm{kg\,m^{-3}})} \quad \text{(Van Wagner 1977)} \tag{2a}$$

$$S_o = R_o \times d \tag{2b}$$

R_o is the critical minimum rate of spread for active crown fire; S_o is the critical mass flow rate for solid crown flame; d is the canopy bulk density.

Van Wagner (1977) used one stand (R1 in Table 1), considered 'an incipient' active crown fire, for model calibration. The observed rate of spread of fire in stand R1 was multiplied by CBD to determine the required mass flow (S_o in Eqn 2b) (Van Wagner 1977). It was apparent that this resulting value was less than necessary for active crown fire so Van Wagner set S_o at a constant value slightly greater ($0.05\,\mathrm{kg\,m^{-2}\,s^{-1}}$) (VanWagner 1977). This established the minimum mass flow value necessary because a slower fuel consumption rate would result in fire behavior similar to the incipient crown fire behavior of R1 (Van Wagner 1977).

For VWfba, we divide Van Wagner's value of $S_o = 0.05\,\mathrm{kg\,m^{-2}\,s^{-1}}$ by the CBD for stand R1 ($0.23\,\mathrm{kg\,m^{-3}}$) (Eqn 3a). The result is a cROS of $0.217\,\mathrm{m\,s^{-1}}$ for stand R1. The cROS is multiplied by the FBA (Table 1) of stand R1, resulting in a product of $0.39\,\mathrm{kg\,m^{-1}\,s^{-1}}$ (Eqn 3b). This new equation gives the mathematical equivalent to Van Wagner's published value using CBD of $S_o = 0.05\,\mathrm{kg\,m^{-2}\,s^{-1}}$, as can be seen more easily after rearranging Eqns 3a and 3b (Eqn 3c):

$$0.05\ (\mathrm{kg\,m^{-2}\,s^{-1}}) \div 0.23\ (\mathrm{kg\,m^{-3}}) = 0.217\ (\mathrm{m\,s^{-1}}) \tag{3a}$$

$$0.217\ (\mathrm{m\,s^{-1}}) \times 1.80\ (\mathrm{kg\,m^{-2}}) = 0.39\ (\mathrm{kg\,m^{-1}\,s^{-1}}) \tag{3b}$$

$$\frac{0.05\ (\mathrm{kg\,m^{-2}\,s^{-1}})}{0.23\ (\mathrm{kg\,m^{-3}})} = 0.217\ (\mathrm{m\,s^{-1}}) = \frac{0.39\ (\mathrm{kg\,m^{-1}\,s^{-1}})}{1.80\ (\mathrm{kg\,m^{-2}})} \tag{3c}$$

The final form of the VWfba model is then:

$$R_o\ (\mathrm{m\,s^{-1}}) = \frac{0.39\ (\mathrm{kg\,m^{-1}\,s^{-1}})}{d'\ (\mathrm{kg\,m^{-2}})} \tag{4}$$

Van Wagner data

After recalibration of S_o, the VWfba model was applied to the rest of the data provided by Van Wagner (1977) (Fig. 2). With exception of the calibration fire R1, all of these fires were observed crown fires. A satisfactory model will have a predicted cROS that is exceeded by the observed rate of spread for the active fires. Inputs for these predictions were taken from Van Wagner's published data. The method of CBD estimation for input to the original VW model was unspecified; the published foliar biomass per unit ground area for these stands is used as FBA input to the VWfba model.

Landscape-level data

We use a database of 2626 FIA plots collected from the Inland Northwest region of the United States (Gillespie 1999). Each of the 40 386 tree records in this database includes the variables of tree diameter, height, percentage live crown ratio, species, and the tree expansion factor (number of trees per hectare that record represents) as well as plot-level variables not used here. FIA routinely collects data on trees, saplings, and seedlings at each plot; however, our database comprised trees at least 7.56 cm (3 inches) in diameter at breast height (DBH, 1.37 m) (USDA Forest Service 1990). The reason for the omission of saplings and seedlings is that the database was originally compiled for research that analyzed the volume growth increment data, which the Forest Service FIA group collects only for trees greater than 7.56 cm (Froese 2003). We do not consider this omission to be important for modeling the propagation of crown fire.

Of the 2760 plots in our database, we only were able to use 2626 plots owing to a lack of conifer species (FVS only calculates CBD for conifer species) (Reinhardt and Crookston 2003).

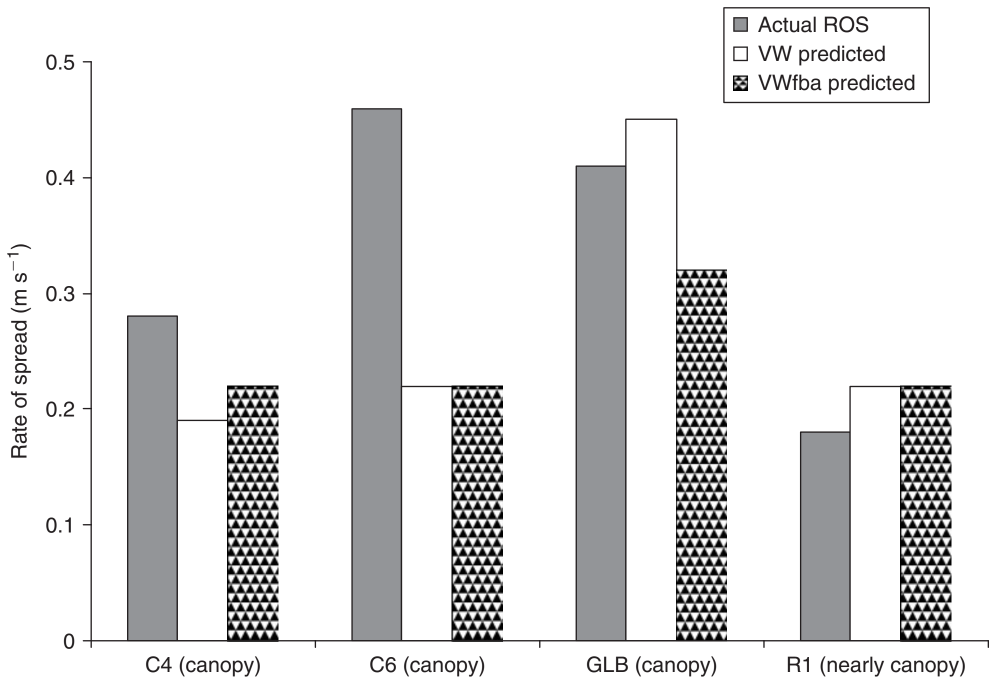

Fig. 2. Summary of Van Wagner (1977) published results and the VWfba recalibration applied to original data. Note that only the VWfba estimate is exceeded by the actual rate of spread in the GLB fire. Actual = observed rate of spread; VW = Van Wagner's published model cROS prediction; VWfba = cROS prediction for the modified model described in the present paper.

Of these 2626 plots, approximately 80% were from the old FIA sampling design and 20% were from the new sampling design. The old design used a cluster of sample points (five, seven or ten depending on location) where all 'in' trees (determined by a 4.9-m^2 ha^{-1} basal area factor prism) >12.7-cm (5-inch) DBH are measured and then an additional sample of up to two trees per species per 5.08-cm (2-inch) diameter class if they are >7.56 cm. The new design uses a cluster of four fixed-area subplots rather than the previously described basal area factor design. The collection of tree data within those plots is identical, with all trees >12.7 cm being sampled, and the subsample of trees greater than 7.56 cm by species and diameter class. A more detailed description of this exact dataset can be found in Froese (2003) and Robinson and Froese (2004).

Statistical analysis

We compared the predictions of the models using so-called two-one-sided tests (TOST), which are tests of statistical equivalence (see Schuirmann (1981) and Westlake (1981) for TOST, and Robinson and Froese (2004) for model validation using equivalence tests). Such tests require the nomination of a range of equivalence, which is a range such that if the observed difference is within the range, the parameters being compared may be considered to be to all intents and purposes identical. Broadly speaking, the null hypotheses for tests of equivalence are of dissimilarity, whereas the null hypotheses of traditional tests are of similarity, or equality. In the present paper, we choose a strict range of equivalence such that $|\bar{x}_{diff} \pm \varepsilon| < 0.138\,\mathrm{m\,s^{-1}}$ ($\pm 0.50\,\mathrm{km\,h^{-1}}$) for cROS, where $\bar{x}_{diff}$ is the observed mean difference between two samples and ε is the minimum range of equivalence. The absolute sum of these two values must be less than the range of equivalence in order to reject the null hypothesis of dissimilarity. The values were chosen as being insignificant ranges of difference from both a management and a modeling standpoint. We used a one-sided type I error rate of 5% ($\alpha = 0.05$), which translates to two times a one-sided α ($2 \times 0.05 = 0.10$) for our TOST test of equivalence. All analyses were performed in the statistical environment R (R Development Core Team 2008).

Our data exhibit light tails, relative to the normal distribution; however, our large sample size lends resistance to departures from normality (Ramsey and Schafer 2002). To verify that outliers were not affecting the results, we removed obvious outliers and reran the TOST. In each comparison of models, removing the outliers made the minimum region of equivalence (which is analogous to the *P*-value) smaller. Hence, the null hypothesis was more clearly rejected with the outliers removed in each comparison and we present our results with all data represented.

Results

The *Results* section comprises two parts; the comparison of model predictions using VWcbd with updated predictions using VWfba for the original data, and a statistical comparison of the cROS for the FIA plots using the three different models.

The VWfba and VWcbd comparison using Van Wagner's (1977) data provide comparable predictions of cROS (Fig. 2). However, VWfba identifies stand 'GLB Active' as exceeding the cROS, and correctly classifies it as an active crown fire, whereas VWcbd does not (Fig. 2). These results provide assurance that

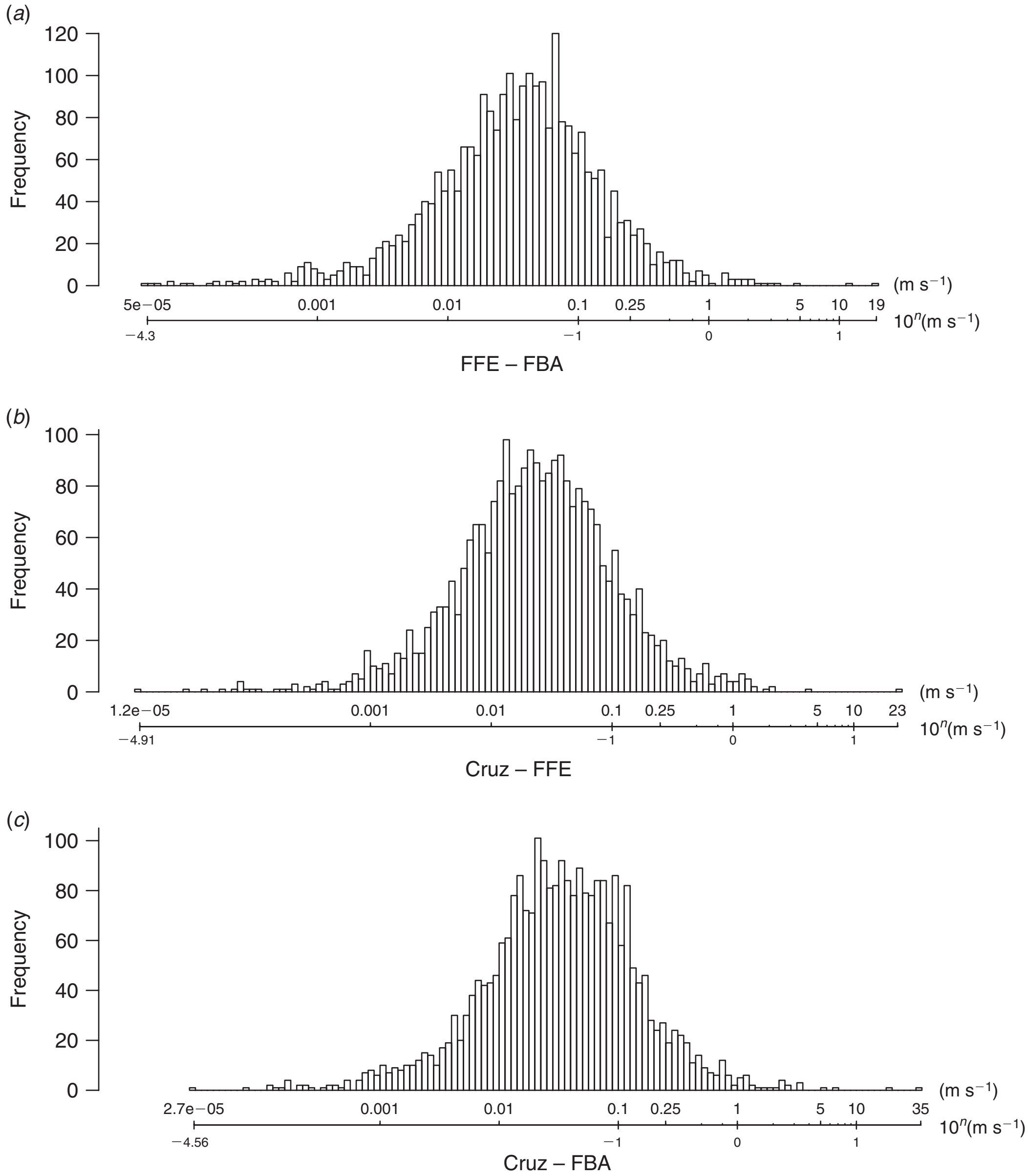

Fig. 3. The $\log_{10}$-transformed absolute differences in critical rate of spread between pairs of models: (*a*) VWcbd-FFE minus VWfba; (*b*) VWcbd-Cruz minus VWcbd-FFE; (*c*) VWcbd-Cruz minus VWfba.

the VWfba method shares the same experimental grounding, and can be shown to be calibrated identically to the original model.

We provide an exploratory summary graphic of the log (base 10) of the absolute plot-level cROS prediction differences that result from the FIA data analysis (Fig. 3). This figure shows that the log of the absolute differences in each comparison is reasonably symmetric and light-tailed. The vast majority of these differences are less than $0.10\,\mathrm{m\,s^{-1}}$.

The mean of the differences between cROS for FIA plots using VWcbd-FFE (VWcbd using the FFE fuel calculation method) and VWfba is only $0.010\,\mathrm{m\,s^{-1}}$ (Table 2), and the null hypothesis of dissimilarity is rejected. The sum of the minimum range of equivalence and the mean of the difference ($0.010 \pm 0.027\,\mathrm{m\,s^{-1}}$) are substantially less than the strict range of equivalence, which lends strong evidence (in lieu of a *P*-value) that the rejection of the null hypothesis is justified (Table 2).

These same patterns are repeated for the comparison of VWcbd-Cruz (VWcbd using the Cruz fuel calculation method) and VWcbd-FFE, though the mean of the difference is larger than the previous comparison ($0.050\,\mathrm{m\,s^{-1}}$) (Table 2). Again, the sum of the difference and the minimum range of equivalence ($0.050 \pm 0.066\,\mathrm{m\,s^{-1}}$) are well within the predefined strict range of equivalence, leading to a comfortable rejection of the null hypothesis. In the final comparison between VWcbd-Cruz and VWfba, the mean of differences is larger than any of the previous comparisons ($0.060\,\mathrm{m\,s^{-1}}$) (Table 2). The sum of this large bias between the models and corresponding large minimum region of

Table 2. Results of the equivalence test for Forest Inventory and Analysis, with $n = 2626$
s.d., standard deviation; FFE, Fire and Fuels Extension; FBA, foliar biomass per unit area; RMSE, root mean squared error

Models compared ($x_a - x_b$)	Mean of difference ($\mathrm{m\,s^{-1}}$) ($\bar{x}_{diff}$)	s.d. of difference ($\mathrm{m\,s^{-1}}$)	H_o: Dissimilarity	Minimum range of equivalence (ε)	RMSE
FFE – FBA	0.010	0.499	Reject	±0.027	0.499
Cruz – FFE	0.050	0.486	Reject	±0.066	0.489
Cruz – FBA	0.060	0.814	Accept	±0.086	0.816

equivalence ($0.060 \pm 0.086\,\mathrm{m\,s^{-1}}$) does not allow a rejection of the null hypothesis of dissimilarity under the strict equivalence scenario. In all but one of these comparisons, we reject the null hypothesis of dissimilarity.

To summarize the results, the rejection of the null hypothesis between VWcbd-FFE and VWfba indicates that these two models are statistically equivalent to each other within a narrow (conservative) range of values $\pm 0.138\,\mathrm{m\,s^{-1}}$. In fact, in our dataset, if the user of the VWfba is comfortable ignoring differences (VWcbd-FFE minus VWfba) between -0.017 and $0.027\,\mathrm{m\,s^{-1}}$, then these two models are equivalent to each other. The average difference between the models shows that VWcbd-FFE cROS will be $0.010\,\mathrm{m\,s^{-1}}$ greater than VWfba.

Likewise, the VWcbd-Cruz and VWcbd-FFE are statistically equivalent to each other within our pre-established conservative test values, but more importantly, they are statistically equivalent to each other if the user is willing to ignore differences (VWcbd-Cruz minus VWcbd-FFE) ranging from 0.016 to $0.116\,\mathrm{m\,s^{-1}}$. In this comparison, on average the VWcbd-Cruz cROS is $0.050\,\mathrm{m\,s^{-1}}$ greater than the VWcbd-FFE. Additional investigation into this result suggests that the cause is the inclusion of the extra branch wood (50% of the 0–6.3-mm branch wood) included in the FFE calculation.

The test of equivalence of VWcbd-Cruz and VWfba failed to reject the null hypothesis. The average difference between these models (VWcbd-Cruz minus VWfba) is $0.060\,\mathrm{m\,s^{-1}}$.

Discussion

Overall, our results are encouraging, and suggest that using VWfba is a plausible strategy that may simplify the deployment of models of crown fire propagation with negligible loss of accuracy.

The VWcbd-FFE and VWfba estimates for the regional FIA data are statistically equivalent to one another, that is, they are well within acceptable ranges of equivalence that we established for these tests. We demonstrated that VWfba is equivalent to VWcbd-FFE in the Inland Northwest when the sampling design of FIA is followed and the data used to describe a 0.40-ha (1-acre) stand, omitting trees less than 7.62 cm DBH. Based on our analysis of comprehensive FIA data, we conclude that the use of VWfba is a reasonable alternative to VWcbd, in particular when compared with VWcbd-FFE, at the overall landscape level. We do not make any statement about the suitability of VWfba for individual stands at this point.

The VWfba provides the lowest estimate of cROS among the three methods (Table 2). The low estimates of cROS result in mean differences of 0.010 and $0.060\,\mathrm{m\,s^{-1}}$; these are interpreted to mean that, on average, the VWfba model estimates the cROS necessary to sustain crown fire to be less than the cROS predicted by the VWcbd-FFE and VWcbd-Cruz respectively. The differences from the consistently higher calculated cROS values of the VWcbd can only be attributed to the use of all available fuel in the VWfba. This must be true, because we have shown that the VWfba and VWcbd models are structurally identical and the inputs differ only in whether a fraction of the total available fuel (Cruz and FFE) or all available fuel (FBA) is used as the input, if we assume that the VWcbd models are identically calibrated to (or with) the original Van Wagner data.

We do not know of data with which to compare these different models in order to determine the 'best' model. What our tests and results show is that VWfba is equivalent in predictive performance to the VWcbd-FFE, disregarding a narrow range of difference that was predetermined to be insignificant from a management standpoint. The VWcbd-Cruz and VWcbd-FFE models are also considered to be equivalent to each other with this same predetermined standard. However, the comparison between VWcbd-Cruz and VWfba has a wider range of differences that must be acceptable for a manager to consider them equivalent.

The VWcbd and VWfba can both be extrapolated between two points on a landscape for use in a spatial fire model if the appropriate stand information is available. Intuition suggests that two stands of similar land area with identical foliar biomass, one with a short dense canopy and the other with a sparse and vertically attenuated crown, will burn differently. However, both models only assess the fuel input in terms of meeting the minimum mass flow rate, or the mass of fuel combusted at any given instant in time per unit of crown fire front.

In practice, using VWcbd in spatial modeling applications, CBD is calculated and attributed to stands with the resultant cROS calculated for the entire stand, without regard to scale. Whether the stand is a pixel or 500 ha, the underlying assumption is that the effects of the vertical dimension of fuel on crown fire propagation are already incorporated in the fuel input. This is a reasonable proposition that could be put forth as an advantage of CBD metrics, although it is not substantiated in the literature. Furthermore, Hall and Burke (2006) found that the FFE method is insensitive to the vertical distribution of foliar biomass, and is more sensitive to the individual crown shapes.

For example, imagine two hypothetical 300-m^2 forested stands, one with a smaller number of trees ('A'), and the other ('B') with a larger number of trees relative to each other, but the foliar biomass between stands is known to be identical. Since the foliar biomass of the trees is directly proportional to the basal area and biomass of the supporting structure of the trees (Smith *et al.* 1997) stand 'A' will have large open grown trees with long, full crowns. This inherently means large inter-tree distances that act as a barrier to crown fire propagation. While in stand 'B' numerous, shorter trees, will result in small inter-tree distances, with less resistance to crown fire propagation.

In these two stands, if the FBA is calculated at the scale of the entire stand (300 m^2), the difference in cROS between both stands would be zero for VWfba. However, if FBA for the entire stand was calculated at a finer grain (e.g. 30-m resolution), then the resulting heterogeneity of the spatial pattern should reflect an inability of crown fire to spread across the large spaces in stand 'A', but still maintain propagating conditions in stand 'B'. In other words, we expect that FBA would better account for variation in spatial distribution of fuels because it can be calculated at less than the stand level.

In comparison, the FFE metric assumes that the running mean takes into account this sort of stand-structure difference. Verification of these assumptions is difficult, if not impossible, and is lacking in the literature.

In a spatial fire model, the VWfba model does not require knowledge about the vertical distribution of fuel across the landscape, only that enough fuel exists between adjacent points to sustain crown fire on that landscape. Future work with the VWfba model may incorporate a number of other parameters to properly adjust for cROS in future experiments, but these coefficients can be interpreted independently of the combustible biomass estimate. This approach leads to a more subtle refinement of the model output independently of the quantity of fuel that is truly available to the advancing crown fire.

We note that FBA can be decomposed into two more primitive terms as follows: FBA = LAI/SLA, where LAI is leaf area index ($m^2\ m^{-2}$) and SLA is specific leaf area ($m^2\ kg^{-1}$). Ultimately, acceptance of the VWfba model may lead to the development of a crown fire propagation model that can be related simply to LAI. This would remove the necessity of knowing the tree species necessary to assign an SLA value. This refinement would provide a practical method to take remotely sensed imagery and convert it directly to a relevant canopy fuel characteristic involving one less step than the VWfba model proposed herein.

In summary, the adoption of VWfba may allow consistent fuel quantifications that are robust to the highly varied canopy structure of forested stands compared with CBD. Furthermore, data collection for VWfba should be much less expensive, and easier to acquire over large scales, if it can be related to remotely sensed measurements. The VWfba recalibration of Van Wagner's (1977) model provides statistically equivalent estimates and is consistent with the original field observations of Van Wagner (1977).

The VWfba model should next be applied to a variety of case studies where estimates of foliar biomass can be obtained for observed crown fires. An example of this sort of validation could be the acquisition of LANDSAT imagery over an area subsequent to a crown fire. Using estimates of foliar biomass derived from LAI and SLA, the resulting VWfba prediction could be compared with fire behavior observations from that fire. This type of field validation removes the necessity of estimating the probable fire spread direction and then placing fuel sampling personnel directly in the path of impending crown fires, allowing the required fire observations to be conducted from a safe distance. Given the lack of literature suggesting that the use of VWcbd adequately provides estimates of the cROS threshold, we would not necessarily expect the VWfba model to accurately estimate cROS in these field trials, but we would expect it to perform as well as the VWcbd model, if reliable CBD data could be collected for comparison.

In the novel 'Flatland' (Abbott 1884), the Sphere found it difficult to accept that simple dimensions can have useful information. The exclusion of height, or crown depth, in a crown fire propagation model does not necessarily reduce the quality of the overall predictions.

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